# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**MAXIMIZING SITUATION AWARENESS: IMPROVING SITUATIONAL AWARENESS WITH GLOBAL POSITIONING SYSTEM DATA IN THE MARITIME ENVIRONMENT**

by

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March 2009

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| REPORT DOCUMENTATION PAGE | | | *Form Approved OMB No. 0704-0188* |
|---|---|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503. | | | |
| **1. AGENCY USE ONLY *(Leave blank)*** | **2. REPORT DATE** March 2009 | **3. REPORT TYPE AND DATES COVERED** Master's Thesis | |
| **4. TITLE AND SUBTITLE** Maximizing Situational Awareness: Improving Situational Awareness with Global Positioning System Data in the Maritime Environment | | | **5. FUNDING NUMBERS** |
| **6. AUTHOR(S)** Ferebee, Michel J. | | | |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Naval Postgraduate School Monterey, CA 93943-5000 | | | **8. PERFORMING ORGANIZATION REPORT NUMBER** |
| **9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)** N/A | | | **10. SPONSORING/MONITORING AGENCY REPORT NUMBER** |
| **11. SUPPLEMENTARY NOTES** The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. | | | |
| **12a. DISTRIBUTION / AVAILABILITY STATEMENT** Approved for public release; distribution is unlimited | | | **12b. DISTRIBUTION CODE** |

**13. ABSTRACT (maximum 200 words)**

The U.S. Coast Guard mission is to daily conduct law enforcement in the dynamic and challenging maritime environment. Rapid advances in technology have the potential to dramatically improve the organization's capacity to conduct this mission. The ability to track and monitor suspect vessels, as well as the law enforcement personnel that board them, is a critical next step in the evolution of Maritime Interdiction. With the development of the Global Positioning System (GPS) and downward trend of GPS receiver costs and their form size, it is now possible to integrate positioning technology with software collaborative tools and wireless networking. The power of collaboration tools and real time positioning data offers the potential to deliver an entirely new and unique level of situational awareness to the law enforcement teams on the water as well as the command and control structure shore side. No longer does VHF radio need to be the sole form of communication between operational personnel and their commands. This thesis discusses the specific methods available for tagging and tracking individuals and vessels and explores the challenges and feasibility of deploying these technologies in the maritime environment.

| **14. SUBJECT TERMS** Global Positioning System, GPS, Situational Awareness, Maritime Domain Awareness | | | **15. NUMBER OF PAGES** 79 |
|---|---|---|---|
| | | | **16. PRICE CODE** |
| **17. SECURITY CLASSIFICATION OF REPORT** Unclassified | **18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified | **19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified | **20. LIMITATION OF ABSTRACT** UU |

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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**MAXIMIZING SITUATIONAL AWARENESS: IMPROVING SITUATIONAL AWARENESS WITH GLOBAL POSITIONING SYSTEM DATA IN THE MARITIME ENVIRONMENT**

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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN INFORMATION TECHNOLOGY MANAGEMENT**

from the

**NAVAL POSTGRADUATE SCHOOL**
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The U.S. Coast Guard mission is to daily conduct law enforcement in the dynamic and challenging maritime environment. Rapid advances in technology have the potential to dramatically improve the organization's capacity to conduct this mission. The ability to track and monitor suspect vessels, as well as the law enforcement personnel that board them, is a critical next step in the evolution of Maritime Interdiction. With the development of the Global Positioning System (GPS) and downward trend of GPS receiver costs and their form size, it is now possible to integrate positioning technology with software collaborative tools and wireless networking. The power of collaboration tools and real time positioning data offers the potential to deliver an entirely new and unique level of situational awareness to the law enforcement teams on the water as well as the command and control structure shore side. No longer does VHF radio need to be the sole form of communication between operational personnel and their commands. This thesis discusses the specific methods available for tagging and tracking individuals and vessels and explores the challenges and feasibility of deploying these technologies in the maritime environment.

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## TABLE OF CONTENTS

# LIST OF FIGURES

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# LIST OF TABLES

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# ACRONYMS AND ABBREVIATIONS

AIS – Automatic Identification System

AP – Access Point

ARAM – Adaptable Radiation Area Monitor

BFT – Blue Force Tracking

C4ISR – Command, Control, Communication, Computers, Intelligence, Surveillance, and Reconnaissance

CENETIX – Center for Network Innovation and Experimentation

CF – Compact Flash

COP – Common Operating Picture

COPT – Captain of the Port

DGPS – Differential Global Positioning System

DHS – Department of Homeland Security

DoD – Department of Defense

DR – Dead Reckoning

EAIS – Encrypted Automatic Identification System

FCC – Federal Communications Commission

FTP – File Transfer Protocol

GCCS – Global Command and Control System

GLONASS – Global Orbiting Navigation Satellite System

GNSS – Global Navigation Satellite System

GPRS – Global Packet Radio Service

GPS – Global Positioning System

GSM – Global System for Mobile Communications

GUI – Graphic User Interface

HVT – High Value Target

IMO – International Maritime Organization

IMU – Inertial Measurement Unit

INS – Inertial Navigation System

IP – Internet Protocol

KML – Keyhole Markup Language

LAN – Local Area Network

LLNL – Lawrence Livermore National Lab

LOP – Line of Position

LOS – Line of Sight

LRIT – Long Range Identification and Tracking

Mbps – Megabits Per Second

MDA – Maritime Domain Awareness

MIO – Maritime Interdiction Operations

NAIS – Nationwide Automatic Identification System

NDGPS – Nationwide Differential Global Positioning System

NLOS – Non Line of Sight

NMEA – National Marine Electronics Association

NPS – Naval Postgraduate School

OLSR – Optimal Link State Routing

PANYNJ – Port Authority New York/New Jersey

PPS – Precise Positioning Service

PTP – Point-to-Point

PTM – Point-to-Multipoint

PVT – Position, Velocity, Time

RFP – Request for Proposal

RHIB – Rigid Hull Inflatable Boat

RTCM – Radio Technical Commission for Maritime Services

SA – Selective Availability

SA – Situational Awareness

SBC – Single Board Computer

SOLAS – Safety of Life at Sea

SIM – Subscriber Identity Module

SPS – Standard Positioning Service

SUSA – Small Unit Situational Awareness

TNT – Tactical Network Topology

UOB – University of Bundeswehr

UTC – Coordinated Universal Time

UWB – Ultra Wideband

VHF – Very High Frequency

VOIP – Voice Over Internet Protocol

WMD – Weapon of Mass Destruction

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# ACKNOWLEDGMENTS

I would like to thank Dr. Alex Bordetsky, Eugene Bourakov and Albert Baretto for their assistance with this journey. I would not have succeeded without each of your support, guidance and encouragement.

To my wife Heather, thank you for being so supportive during this past two-year endeavor. The continued sacrifice and support you and Logan provided on a daily basis make graduation possible. Thank you, I love you very much.

To my new son Logan, I cannot wait to share with you the wonders that await you. I can only begin to imagine the great things you will accomplish in your future.

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# I. INTRODUCTION

## A. BACKGROUND

The United States Coast Guard has a rich and storied history and can trace its roots to 4 August 1790. On this date, the first Congress authorized the construction of ten vessels and created the Revenue Cutter Service. Their mission was to enforce tariff and trade laws and to protect the nation from smuggling activities. This service was subsequently merged with the Life-saving service by an act of Congress in 1915 and has thereafter been known as the U.S. Coast Guard. Throughout its long history the service has grown and expanded its missions to meet the needs of the country. As one of the Nations five military services, the Coast Guard is the only armed service that provides general domestic law enforcement authority and is charged with the protection of the public, environment and U.S. economic and security interests in the maritime domain. Although the agency has transformed itself from its early roots, the primary mission has always remained the defense and protection of the United States and her citizens.

From the early days of prohibition, the Coast Guard has been the primary maritime law enforcement agency and operated under the Treasury Department for almost 177 years (Johnson, 1987). With the implementation of the 12-mile offshore fishery zone in 1967 and the creation of the Fisheries Conservation and Management Act in 1976 with its 200-mile Exclusive Economic Zone and responsibility for the Outer Continental Shelf, Coast Guard responsibilities continued to grow. Current U.S. maritime jurisdiction includes some 3.5 million square miles of ocean area and 98,000 miles of coastline (Maritime Strategy for Homeland Security, 2002). In the years following the 9-11 attacks the Department of Homeland Security (DHS) was created to meet the growing challenges of domestic security. After nearly 36 years with the Department of Transportation, the Coast Guard was realigned under DHS in 2003. Since this shift to DHS the Coast Guard has worked hard with its DHS partners to enhance Maritime Domain awareness through the use of innovation and technology to meet the security challenges of the twenty-first century.

According to a 2008 Coast Guard summary of facts the service, on a daily average:

- Completes 31 Port State Control safety and environmental exams on foreign vessels.
- Issues 102 Certificates of Inspection to U.S. commercial vessels
- Administers 25 International Ship and Port Facility Security Code vessel exams
- Boards 193 ships and boats

## B. STATEMENT OF PROBLEM

Maritime Domain Awareness (MDA) continues to be a top priority for the U.S. Coast Guard. The ability to monitor and track vessels while incorporating this positioning data into a situational awareness tool would greatly enhance their ability to monitor vessel traffic and personnel. The vast amount of ocean areas and large number of maritime traffic makes this challenge difficult in the best of situations. As the U.S. Coast Guard works to meet the maritime security challenges posed by a post 9-11 world, resources are stretched even further. The need to enhance situational awareness for the operators in the field and the command and control structure continues to grow. The organization is working hard to develop new Command, Control, Communication, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) systems to facilitate this need. One area of concern is the lack of self-updating and reliable positioning data of law enforcement personnel and the suspect vessels they board and track. Although perhaps oversimplified, the challenges posed by this dilemma can be summed up in three parts. First, how to track boarding teams and vessels; second, how to transmit this data; and third, what are the best tools to incorporate this data into a robust and user-friendly situational awareness tool. The challenge posed by these issues is often exacerbated by the nature of the marine environment and the diverse scenarios law enforcement personnel face. The Coast Guard is working to answer some of these questions with the development of the Nationwide Automatic Identification System (NAIS). The goal of NAIS is to enhance MDA with AIS data (e.g., vessel location, course and speed) that will

feed into the Maritime Common Operating Picture (COP). This data provides real time tracking of vessels registered in the AIS program as well as Blue Force Tracking (BFT) capabilities.

The challenge that remains is the tracking of Coast Guard personnel and vessels either too small to require AIS registration or vessels intentionally subverting the system either through non-participation or broadcasting invalid information. While at sea, boarding teams are often deployed from a larger cutter via the ships Rigid Hull Inflatable Boat (RHIB) or transported via a small boat from a shore-based station. In almost all cases, communications are relayed to the supporting vessel via VHF-radio and do not support the transmission of Global Positioning Data (GPS) data. Even if personal individual GPS data was to be transmitted, position accuracy is often degraded as personnel descend below the decks of larger vessels into GPS denial areas. The support vessel is forced to rely on personnel status and generalized location information passed over voice communications. In turn, the support vessel passes on the overall status of boarding and vessel location to their shore command. The method of communication and level of detail varies depending on the platform size and the onboard communication suite. For example, a station small boat will have significantly less communication ability and range then a larger cutter. Smaller units will relay positioning information of target vessel via voice to the parent command where a larger platform may have the ability to transmit tracking data of vessels over satellite links via the Global Command and Control System (GCCS). While pier-side, communication is relayed primarily back to the command elements via commercial cell phone. At no time, in either case do the boarding teams have the ability to monitor each other’s position or automatically transmit position data into any type of situational awareness tool.

In the case of smaller vessel boardings, situational awareness between team members is generally no longer an issue. The vessels smaller layout enables teams to remain in contact with each other either via radio or voice. GPS denial areas are also greatly reduced and generally not an issue. The bigger issue is from a command and control point of view. Is it possible to either track a suspect vessel covertly or while in a high-speed pursuit? If this positioning data is available, can it be fed into a situational

awareness tool that can be used to monitor and coordinate additional assets? The Coast Guard is currently deploying Encrypted Automatic Identification System (EAIS) on all of their cutters and standard boats to answer the question of BFT. This data is fed into the Maritime COP and enhances situational awareness but still lacks data of suspect vessel and law enforcement personnel.

As technology advances, leveraging new tools to improve performance and enhance the safety of Coast Guard personnel is critical. In today's environment of heightened threats and global terrorism, boarding teams must have the ability to monitor the movements and status of team members and command elements need real-time positioning information. It is critical to overcome the GPS denial problem posed by large vessel boarding's and the tagging/connectivity challenges associated with smaller vessels. The ability to tag and track personnel and vessels regardless of size and location will greatly enhance situational awareness for everyone. Not only does electronic tracking offer increased security for personnel it alleviates the need to exhaust resources for simple monitoring activities and provides the ability to coordinate interception efforts. Great strides have been made in the area of GPS tagging and tracking and the exploration of collaborative tools to utilize this data. The Naval Postgraduate School Center for Network Innovation and Experimentation (CENETIX) continues to explore methods to enhance situational awareness in the maritime domain through the use of GPS tagging and tracking techniques. This thesis will explore the effectiveness of these tagging and tracking techniques and feasibility of incorporating them into the U.S. Coast Guard C4ISR suite.

## C. OBJECTIVES

As threats to U.S. national security mount, the Coast Guard struggles to stretch its finite number of response resources to meet all of the service missions. The service needs to utilize technology to meet these new challenges while maintaining excellence in the traditional missions of Maritime Safety, Protection of Natural Resources and Maritime Mobility. Advances in GPS and communication technology offer the promise of providing new levels of situational awareness. This thesis will explore GPS tracking

techniques and the ability to transmit this data into a situational awareness tool. Data gathered from Tactical Network Topology (TNT) and Maritime Interdiction Operations (MIO) field studies will be evaluated to determine their viability to meet this critical need.

## D. THESIS ORGANIZATION

This thesis is structured in the following manner: Chapter I provides a broad overview of the Coast Guard and the current challenges facing the organization, related to Maritime Interdiction, and the benefits offered by the capability to track law enforcement personnel and target vessels. Chapter I will also provide a brief overview of the basic objectives of this thesis. Chapters II and III explore the fundamentals of GPS, how the system works and the challenges associated with tagging and tracking. Chapter IV explores the potential for transmitting this data and the different communication options available. Chapters V and VI provide detailed data on GPS tagging and tracking from TNT MIO field experiments and explains the performance of collaboration tools and positioning tools can work together. Chapter VII concludes with final analysis, lessons learned and recommendations for follow-on research.

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# II. THE GLOBAL POSITIONING SYSTEM

## A. BACKGROUND

There are currently two Global Navigation Satellite Systems (GNSS) in existence, the U.S. Global Positioning System (GPS) and Russian Global Orbiting Navigation Satellite System (GLONASS). Galileo, a third GNSS is currently being deployed by the European Space Union and is expected to be operational by 2013. This paper will focus on the U.S. GPS system.

The U.S. GNSS was developed by the Department of Defense and evolved out of a joint project between the U.S. Air Force and U.S. Navy in the 1960s. The system is based on the ancient navigation idea known as trilateration. Trilateration is the determination of position based on the measurement of distance from a previously known point. A range is taken from each signal or fixed mark and a circle is drawn. With three lines of position (LOP), we can determine a fairly accurate position based on where the three arcs or LOP's meet, giving us a "fixed" position (See Figure 1).

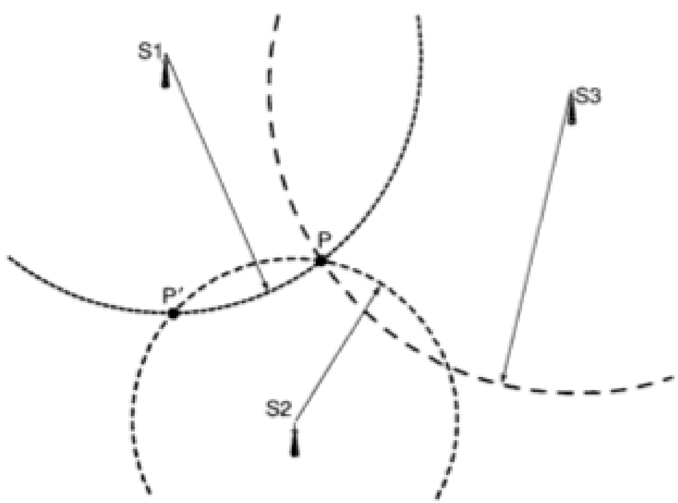


Figure 1. Trilateration (From Misra & Enge)

For space-based transmitters, each range measurement will specify a surface of position or sphere. Where these spheres intersect indicate the position on earth. In order to measure the signal time, it is important the satellites and receiver clocks are synchronized (Misra & Enge, 2001). “The advent of satellites, atomic frequency standards, spread spectrum signaling and microelectronics are the key developments in the realization and success of GPS.” (Misra & Enge, 2001). The result is that each receiver has the ability to provide the user with a three dimensional location (latitude, longitude and altitude) plus the time (National Space-Based Positioning, Navigation, and Timing Coordination Office, 2009.)

## B. SEGMENTS

### 1. Space Segment

The Space segment consists of the 24 orbiting satellites that provide the user on the ground a minimum visibility of four satellites at any given time (See Figure 2). The first satellite was launched in 1978 and after a total of 24 satellites were placed into orbit the system was declared operational in 1995. Each satellite has a twelve-hour orbit around the earth and the satellites are positioned in 6 orbital planes; each circular orbit has a radius of 26,560 km. The number of total satellites in orbit is currently 31 (U.S. Naval Observatory, 2009). The Air Force continues to manage and upgrade the system with new satellites causing the total number of satellites in orbit to fluctuate as systems are taken off line for maintenance and upgrades; however, the primary constellation of 24 satellites remain constant.

Figure 2. GPS Satellite Orbital diagram (Retrieved February 2009, from http://www8.garmin.com/aboutGPS/))

### 2. Control Segment

The Control segment is operated and controlled by the U.S. Air Force 50th Space Wing’s 2nd Space Operations Squadron out of Schriever Air Force Base, Colorado. From the master control station the Air Force controls five monitoring stations and three antennas positioned around the world to monitor and control the GPS satellites (U.S. Coast Guard Navigation Center, 2009). The information gathered by the ground stations is transmitted back to Colorado where precise satellite orbit positions are calculated and transmitted back to the satellites via the ground antennas.

### 3. User Segment

The User segment relates to the receiver side of the system for both military and civilian applications. As prices drop and technology expands, GPS receivers have become smaller and cheaper than ever imagined when the navigation system first came on line. These receivers are now commonplace and can be found in phones, automobiles and even small hand held devices for under $100. The military applications for GPS receivers have also expanded and are now integral to every facet of military operations.

## C. SIGNALS

The Department of Defense provides the GPS Standard Positioning Service (SPS) for civil and scientific use. The SPS service is broadcast on the L1 frequency and operates at 1575.42 MHz that contains a Course Acquisition C/A code. The DoD also broadcast a second encrypted Precise Positioning Service (PPS) signal referred to as the P(Y) code. This encrypted P(Y) code is transmitted on the L1 frequency and a second encrypted P(Y) code is broadcast on the L2 frequency at 1227.60 MHz for DoD authorized users. The government is currently modernizing the GPS program. Under this revitalization two new civil signals will be added, L2C and L5 (See Figure 3). The L2C signal is designed to provide a number of advantages over the sole use L1 signal. When these two signals are used in conjunction it will reduce costs of dual-frequency civil GPS receivers and allow for correction of ionospheric time delay errors. Theses errors cause the largest degradation of positioning accuracy in the current signal (Qaisr & Dempster, 2007). These signals will boost signal strength providing improved access indoors and in obstructed areas. The L2C signal will be broadcast on the L2 carrier and is currently being broadcast by 6 IIR satellites. In 2005 a new Lockheed Martin GPS 2R-M1 (IIR-14) GPS was launched. Once this modernization is complete it will make for easier signal acquisition and improve tracking performance. Currently there are 6 of these satellites in orbit. The L2C signal will be broadcast by 24 satellites by 2016 and the L5 signal by 2018. The current transition date to full operation capability is Dec 31, 2020.

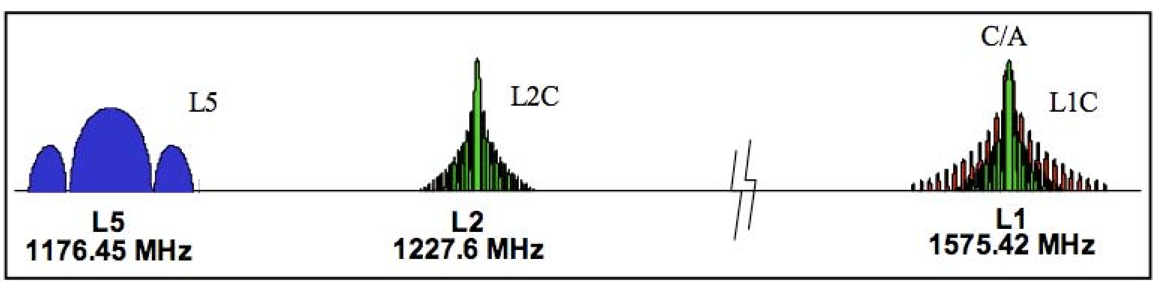


Figure 3. Modernized GPS Frequency (Retrieved February 2009, from http://pnt.gov/public/docs/2006/modernization.pdf)

## D. ERRORS

### 1. Selective Availability

The most significant error source in the GPS signal was intentionally introduced by the DoD and is referred to as Selective Availability (SA). SA was the intentional falsification of the satellite time stamp and or orbit data imbedded in the L1 signal. This intentional error was turned off in 2000. SPS currently provides an accuracy rate of 100 meters horizontally and 156 meters vertically and time transfer to UTC within 340 nano seconds (U.S. Naval Observatory, 2009).

### 2. Ephemeris and Clock Error

GPS satellites are constantly transmitting orbital data referred to as Ephemeris data and internal clock parameters. The Control Segment evaluates this information and values are used to determine a satellite position, velocity and time. “A prediction model is then used to generate the ephemeris and clock data and uploaded to the satellites” (Misra & Enge, 2001). The satellites will then transmit this data to the GPS receivers in the form of a navigation message providing receivers the information needed to determine their position. As satellite orbits shift and minor errors with the internal clock arise, minute positioning errors are introduced known as “ephemeris” errors. These errors will grow as the data becomes older. The Control segment works to minimize these errors by updating the navigation data every 3 hours.

### 3. Signal Propagation Error

Satellite signals travel between 20,000 km and 26,000 km depending on the satellites current position. The majority of this distance is covered in the vacuum of space where the signal is unaffected. However, as it enters the earth atmosphere it encounters resistance. As it a height of approximately 1000 km above the earth it will enter a field of charged particles known as the ionosphere. Following passage through the ionosphere it will enter an electrically neutral gaseous atmosphere known as the

troposphere at approximately 40 km (Misra & Enge, 2001). Both the ionosphere and troposphere alter the velocity and direction of the signal. This phenomenon is known as refraction as is illustrated in Figure 4.

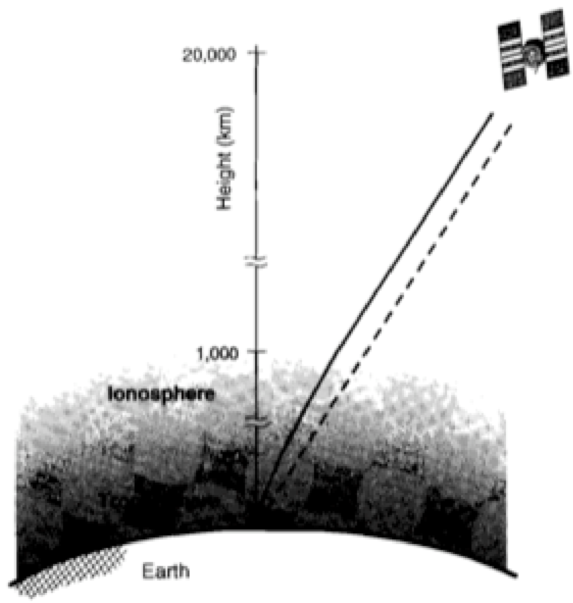


Figure 4. Refraction of GPS signal as it enters atmosphere (from Misra & Enge)

This refraction will alter the speed of the signal and subsequently alter the travel time of signal. This introduces errors when attempting to determine range of satellite when determining position. With the introduction of a second civil signal as outlined in the GPS modernization effort above, dual frequency receivers will be able estimate this delay and reduce the error effect of the ionosphere.

### 4. Multipath Error

Multipath error is introduced when multiple satellite signals are received. This occurs when the signal (radio wave) reflects off an object. This can be a frequent occurrence in cities when the GPS receiver is located between or inside buildings or structures. Signals will bounce of these structures and take a multipath line from the satellite to the receiver verses a direct line of sight path. Because the multipath signal has been reflected, its time to the receiver is altered and the signal strength is generally

weaker than the direct signal. As a satellite becomes lower in the sky, the signal strength weakens resulting in an increase in multipath signals. Depending on the sophistication of the GPS receiver, these multipath signals are filtered out. However, if the receiver becomes confused by a large number of these reflected multipath signals, it can introduce error in the positioning data (See Table 1).

| | |
|---|---|
| Ionospheric effects | ± 5 meters |
| Tropospheric effect | ± 0.5 meter |
| Satellite internal clock error | ± 2 meters |
| Shift in satellite orbit | ± 2.5 meters |
| Multipath effect | ± 1 meter |
| Calculation and rounding errors | ± 1 meter |

Table 1. GPS measurement errors (Retrieved February 2009, from http://www.kowoma.de/en/gps/errors.htm)

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# III. POSITIONING ERROR REDUCTION AND MITIGATION OF DENIAL AREAS

## A. DIFFERENTIAL GPS

As outlined in previous chapter, GPS positioning data is subject to multiple errors. If a single GPS receiver is to be used, the only way to reduce error even further is to use "…code-based pseudoranges[1] perhaps smoothed by carrier phase" to reduce errors even further (Misra & Enge, 2001). In order to reduce the error for the SPS user, the GPS receiver must shift from single-receiver autonomous positions to differential GPS referred to as Differential GPS (DGPS). In an attempt to reduce these errors in the maritime domain, a DGPS network has been deployed.

DGPS is based on the concept that errors for each GPS receiver are similar and the closer receivers are to one another, the closer the errors. As receivers increase in distance and time from one another, this correlation diminishes and the GPS receivers are said to become 'decorrelated'. If the position of a GPS receiver is known, then the combined source of errors (satellite clocks and ephemerides, ionospheric and tropospheric delays, multipath and carrier noise) can be estimated for each satellite within its range. This is valuable data and because of the correlation of errors between GPS receivers this error correction can be used by other GPS receivers in the area to correct their own errors. In order for DGPS to offer real time correct positioning data, the GPS receiver would need to be in close proximity to the known GPS reference station. As the distance increases between receivers so does the time required for updated correction to be received. This time delay is referred to as latency. So, the closer a receiver is to the reference station, the more accurate the positioning data.

DGPS reference stations compute their error corrections and broadcast these differential corrections on a radio link approximately every 30 seconds (Hall, 1996). DGPS configured receivers are then able to receive this data and apply the corrections to

[1] Pseudorange is the first-approximation measurement of the distance between a satellite and GPS receiver.

their own positioning data. In the maritime domain this link was developed by the Radio Technical Commission for Maritime Services (RTCM) and defines the data message and an interface between the data link receiver and the DGPS receiver (Misra & Enge, 2001). The U. S. Coast Guard operates the Maritime Differential GPS service utilizing two control centers and 87 remote broadcast sites (U.S. Coast Guard Navigation Center, 2009). Differential data is broadcast as a Type 9-3 correction messages in the RTCM SC-104 format from marine radiobeacons (See Figure 5) to improve the accuracy of normal GPS. This correction message is transmitted in the 285 to 325 kHz band. A DGPS receiver incorporates two interfaced receivers with a display, a radiobeacon and a GPS receiver capable of applying differential corrections. Latency is primarily a function of distance and baud rate, although processing speed of receiver also plays a small role. There are 210 bits in a Type 9-3 message (three satellites corrected) and latency is generally between 2 to 5 seconds (Hall, 1996). The Coast Guard DGPS Service provides 10-meter accuracy in all established coverage areas. These coverage areas include coastal coverage for the continental U.S., the Great Lakes, Puerto Rico, portions of Alaska, Hawaii and a large part of the Mississippi River Basin (U.S. Coast Guard Navigation Center, 2009).

Figure 5. U.S. Coast Guard DGPS Radio Beacon (Retrieved March 2009, from http://www.navcen.uscg.gov/dgps/default.htm)

The Coast Guard is also responsible for a newly implemented Nationwide DGPS (NDGPS) system. This system's goal is to extend the same Maritime DGPS position accuracy inland. The Coast Guard currently operates and controls 38 NDGPS sites and continues to expand (U.S. Coast Guard Navigation Center, 2008). Although this does not impact the maritime domain it does reflect an increasing trend to improve accuracy and availability of GPS.

## B. GPS DENIAL AREAS

Despite the increased accuracy of DGPS, a major obstacle to tracking of personnel in the maritime domain is the GPS denial area. Denial refers to the degradation or loss of satellite signal. The entire GPS system is susceptible to this signal loss due to the low transmission power of the individual satellites. Currently the RF power of a satellite antenna is approximately 50 watts. This corresponds to a received power level of 160dBw for the C/A code, -163 dBW for P(Y) code on L1 and -166 dBW for P(Y) code on L2 (Misra & Enge, 2001). This low power output makes it difficult to receive a strong signal in any type of obstructed area. With the loss of a signal, GPS receivers no longer have the ability to update their current position. This denial of service can be the result of terrestrial surroundings such as urban areas with large buildings or deep valleys and caves that restrict the line of sight between receiver and satellites. Man-made jamming devices using radio interference, or unintentional jamming from malfunctioning electronic equipment, can also artificially introduce denial areas. Whether intentional or unintentional, jamming involves transmitting a radio signal on the same frequency utilized by the satellite to drown out the satellite signal. In the maritime environment denial areas are generally encountered below the decks of ship where the physical structure of the vessel inhibits the satellite signal from reaching a GPS receiver. The net effect of this signal denial is the user is no longer able to rely on their GPS receiver to maintain an accurate and current position. Currently, the most promising research involving GPS denial areas involves inertial navigation systems. Inertial navigation is

fused with GPS data to augment positioning errors due to weak or lost satellite signals. Inertial navigation measures movement to track position working off the last known GPS position.

## C INERTIAL NAVIGATION

As a GPS receiver enters a denial area, the ability to receive satellite signals becomes compromised. Research is currently being conducted to offset this loss of positioning data through the fusion of Inertial Navigation Systems (INS) and Kalman filters. INS relies on knowledge of the initial position, velocity, and attitude as a base point. As the receiver enters a denial area, it will utilize the last known GPS position as its base point. From the base point, the inertial sensors measure rotation rates and accelerations, which are vector-valued variables (Grewal, Weill & Andrews, 2001). These sensors constitute a gyroscope for measuring rotation (rate gyroscopes measure rotation rate and displacement gyroscopes measure rotation angle). Accelerometers measure acceleration. These sensor components help to estimate position based velocity, attitude and attitude rates and collectively are referred to as an Inertial Measurement Unit (IMU). The second part of the INS system is the navigation computer that measures the input from the sensors and calculates data to estimate position. The accuracy of these estimates are enhanced through the use of a Kalman filter. A Kalman filter is a set of mathematical equations that make an "extremely effective and versatile procedure for combining noisy sensor outputs to estimate the state of a system with uncertain dynamics" (Grewal et al., 2001). As a recursive type of filter it does not require a complete history of positioning information. It combines all the current sensor data with the previous prior positioning estimate to provide current position while minimizing estimation error.

Inertial Navigation systems generally consist of two types; gimbaled and strapdown. In a gimbaled system, at least three gimbals are required to isolate the subsystem from the host rotations around three axis, referred to as roll, pitch and yaw axes (Grewa et al., 2001). A fourth gimbal is required for a host with full freedom of movement around an axis like an aircraft. With a strapdown system the internal sensor

cluster is literally strapped to the host without the additional gimbals utilized in the previous mention to isolate the hosts movement and holds the most promise for personal GPS/INS integration.  The system computer integrates the full six-degree of freedom equations of motion (Grewal et al., 2001).

As with any method of estimation, there is a drawback.  The major Achilles heel of INS is positioning errors grow linearly over time.  As the period between GPS position updates lengthens, the margin of error grows with the INS calculations.  Despite this weakness, INS's biggest advantage in a denial area is that the system utilizes internal accelerometers and gimbals to monitor movement, thus requiring no external input.  This makes it ideal for enclosed or restricted areas that may hinder the reception of external signals.  CHI Systems has developed an interesting application utilizing this concept called Small Unit Situational Awareness (SUSA) system.  SUSA is a "man-portable tracking and command collaboration system" Each user is outfitted with gear (See Figure 6) comprising of a handheld computer, GPS capability, an inertial navigation unit, and a two way communications system (Geospatial-solutions, 2008).  With a communication system that offers both Wi-Fi and UHF radio to communicate with other users. The best benefit of this type of navigation system is it is self-contained and can be utilized in any type of zone or area with no pre-staged systems put in place.  The upside is the user can monitor their own position; the downside is that without a backbone network in place, users may encounter difficulties transmitting positions back to their command as they descend below decks. The inability to transmit outside the skin of a ship would require the augmentation of some type of robust network and will be explored later in the paper. The command and control feature of the system provides the ability to overlay position over satellite imagery.


Figure 6. SUSA gear (Retrieved March 2009, from www.gpsworld.com/gpsmg/article/articleDetail.jsp?id=580475)

## D. RELATIVE NAVAGATION

Relative navigation is the concept of calculating position based on your relative position in relation to a known fixed position. This type of navigation has the potential to offer precise navigation while transiting through a denial area. Relative navigation is accomplished by leaving a GPS receiver in the open where it can receive satellite updates while the user enters into a denial area. As the individual transits through the denial area a ranging device such as a radar would continuously sweep the GPS receiver location providing updated range positions on an x and y axis. This information can then be calculated to give the user an accurate position. This type of navigation is being explored for autonomous vehicles but is not currently seen as a practical solution for the individual user. While the concept has potential, the hardware requirements in terms of weight and power requirements do not make this a feasible option for the personal user. Perhaps, as technology advances, this idea can be revisited.

# IV. TRANSMISSION CHANNELS AND SA MULTI AGENT SYSTEM

## A. RADIO COMMUNICATION LINKS

In order for positioning data to provide value to anyone other than the user, the ability to transmit must be available. With position data available on the network, situational awareness is enhanced. Fortunately, GPS data is very small and requires minimal bandwidth. The difficulty lays in the ability to establish an open communication channel. In a GPS denial area an Inertial Navigation System may solve the positioning problem but the user is still faced with the difficulty of transmitting and receiving position data to team members within the ship and the command structure outside the ship. This is also true in non-denial areas though less problematic. A communication link must be established between team members and the command structure to facilitate the back and forth flow of information. As it is impractical to run wires throughout a ship or across larger stretches of water, a wireless network utilizing a radio communication link is required.

Experimentation is ongoing as to what type of radio links is most viable but the basic requirements remain the same. Radio links will consist of a transmitter, receiver and propagation channel as detailed in (See Figure 7). The characteristics of the link will depend on the conditions of radio propagation in the different kinds of environment encountered. The propagation will be influenced by obstructions surrounding the antennas and existing environmental conditions. The frequency band is one of the main characteristics for predicting the effectiveness of the radio communication links under consideration (Blaunstein & Christodoulou, 2007).

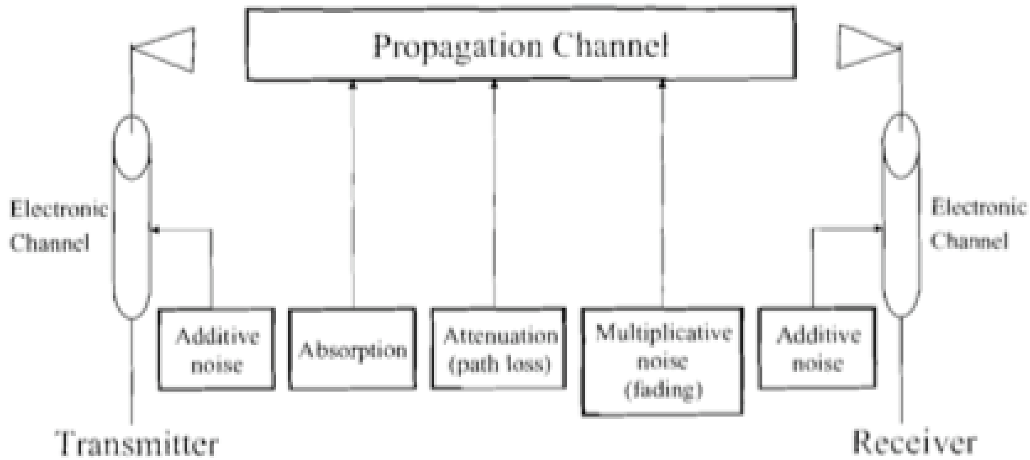


Figure 7. Wireless Propagation Channel (From Blaunstein & Christodoulou)

## B. LINE OF SIGHT

Generally, the simplest radio link relies on Line of Sight (LOS). LOS communications function as the name implies. The receiver and transmitter require a physical line of sight between each other in order to communicate. As the distance increases between receiver and transmitter so does the strength of signal, commonly referred to as path loss. The GPS system is a LOS network. When the GPS receiver can no longer see the satellite we have a denial zone. The LOS issue manifests itself when establishing radio links from the interior of large ships and can make setting up a communication channel difficult. This LOS problem is prominent during boardings of large ships that have several obstructions such as bulkheads and multi-level decks that reflect and absorb radio waves limiting range and effectiveness of radio networks. The Naval Postgraduate School (NPS) CENETIX lab continues to conduct tests to determine the best way to extend the wireless network into these restricted LOS areas with the focus of transmitting data, video and voice communications. Adding positioning data to this link is the next step in the evolution to enhance Situational Awareness. This thesis will exam these links to determine which link offers the best solution.

## C. WIRELESS MESH NETWORK

Wireless Mesh Networking provides the ability to quickly deploy an ad-hoc self-forming and self-healing Local Area Network (LAN). The biggest advantage of mesh networking is it decentralizes the traditional client-server configuration and reduces the impact on Non Line of Sight (NLOS) (Klopson & Burdian, 2005). With a standard wireless network, every node must reach back and share bandwidth with a singe access point. A standard wireless network is limited to the range of the Access Point (AP) and the entire network is vulnerable if the AP goes down. With mesh networking all access points can connect to other stations within range. Additionally, the data has the ability to travel through each node giving each node the ability to act as both a router and a repeater (Carpenter, 2008). This allows the network to grow exponentially as nodes are added allowing data to hop from one node to another. This process greatly increases the range over a standard wireless network. There is no limitation on the type of data and can be in the form of voice, utilizing Voice Over Internet Protocol (VOIP), GPS data, video or any other type of data packets that might normally transmit over a network and is limited only by bandwidth. A mesh network provides the ability to establish connectivity in areas that may otherwise be blocked from LOS obstructions such as ship decks and bulkheads. For example, a wireless access point may be set up on the deck of a ship, but the signal may not penetrate below deck. With a mesh network, nodes can be established below the decks providing jumping points and allowing network access in areas that may otherwise be unavailable. The mesh network is self-healing, allowing the network to continue operating even if a node goes down. If a node does happen to go down, the network is able to re-route traffic to bypass the inoperable node, providing continued connectivity. Currently mesh network devices are not standard based and there are several software routing algorithms available. NPS utilizes the Optimal Link State Routing (OLSR) protocol and has been effective in routing data and video.

## D. ULTRA-WIDEBAND

Ultra-Wideband (UWB) technology is loosely defined as any wireless transmission scheme that occupies a bandwidth of more than 25% of a center frequency, or more than 1.5GHz (Forester, Green, Somayazulu, & Leeper, 2001). This technology is not new and has been implemented in radar-based application since the 1980's. The military developed many of these early systems to take advantage of UWB ability to "see through" objects. UWB ability to penetrate walls comes as a result of its lower frequency components. Lower frequencies have the characteristic of being able to pass through walls because the length of the wave is much longer than the material that it is passing through. This is opposite of higher 802.11 wireless frequencies that tend to bounce off of walls. The UWB ability to propagate through solid materials makes it an intriguing technology in terms of the maritime environment. In the search for a communication channel to process positioning data, UWB offers an interesting choice when below deck and surrounded by steel.

Recently, the commercial sector has been looking at UWB because of its low power, low cost, high data rates and extremely low interference. It differs from conventional narrowband wireless communications, as it does not rely on a single frequency. Instead UWB spreads signals across a wide range of frequencies. Trains of pulses replace the sinusoidal radio wave at hundreds of millions of pulses per second (Ghavami, Michael, & Kohno, 2004). One of the benefits derived from this low-power spectral density is the low probability of detection. The second benefit is the ability to avoid the issue of multipath. As described earlier in the paper, multipath is the phenomenon where the signal from transmitter to receiver takes various paths. This is generally caused by obstructions and result in the radio signal bouncing. With UWB, because of the extremely short pulse widths, if these pulses can be resolved in the time domain then the effects of multipath can be mitigated (Ghavami et al., 2004). This is a key benefit when operating below the deck of a ship where the bulkheads and decks bounce and reflect traditional radio waves.

Lastly, speed of data transmission favors UWB. Although GPS data only requires a minimal amount of bandwidth it is an important factor to consider when looking at the larger communication picture. Ideally, a communication channel will be set up on a network that is able to facilitate every aspect of the command and control architecture. UWB currently has the ability to reach data transfer rates approaching wired Ethernet at 480 Mbits/second (Ghavami et al., 2004). A UWB network can ideally handle not only data but voice and video transmission as well. A network that can simultaneously meet these goals has the best chance of providing a truly dynamic picture with the ability to enhance situational awareness. A word of caution is warranted when integrating GPS receivers and UWB as the UWB signal has the potential to interfere with GPS receivers. The Federal Communications Commission (FCC) recognized this fact and specified spectral masks for different applications, which show the allowed power output for specific frequencies to mitigate these interferences. The FCC currently restricts UWB communication systems between 3.1 GHz and 10.6 GHz (Federal Communications Commission, 2001).

## E. GPRS

General Packet Radio Service (GPRS) is a standard for wireless communications that provides the ability to transfer data packets at speeds up to 115 kilobits per second. These bit rates are sufficient to support data applications like Web surfing, compressed video and File Transfer Protocol (FTP). The GPRS specification was published in 1997 and is designed to give mobile users the ability to send and receive data over an Internet-Protocol (IP) network. Eugene Bourakov, Senior Researcher at NPS, has effectively demonstrated this capability by developing and installing an application developed in the Java Platform Micro Edition known as a MIDlet onto a commercial Blackberry phone. The Blackberry device transmits GPS data in the National Marine Electronics Association (NMEA) file format. The NMEA specification was developed to define the interface between marine electronic equipment allowing them to send information to computers and other marine equipment. GPS receiver communication is defined within this specification and data includes position, velocity and time (PVT) as computed by the

GPS receiver. This GPS data is transmitted over the GPRS network via Internet to the NPS server. The GPS data is then converted into the Google Earth KML (keyhole markup language) file format. This allows for real-time tracking within the CENETIX Resource Portal interface with the Google Earth application. These KML files are stored within the CENETIX Situational Awareness (SA) Replay Control Portal where archived files can be displayed and replayed within Google Earth for future analysis. This provides real-time tracking information to anyone authorized access to the network. It also has the ability to store these waypoints for further evaluation and replay. GPRS services are classified into 2 main groups. The first group: Point-To-Point (PTP) for connection to an IP network or connectionless oriented for connection to a packet data network such as X.25. The second group is Point-to-Multipoint (PTM) that allows for multicast services. A *class A* mobile station can support both GPRS and Global System for Mobile Communications (GSM) services simultaneously allowing a portable device such as a smart phone to become very potent device (Tabbane, 2000).

GPRS is becoming common is smart phones and can be easily incorporated into mobile computing devices through either internal components or commercially available PC cards. NPS has successfully demonstrated the power of combining GPS and GPRS enabled devices to tag and track vehicles and vessels. One of the great benefits of GPRS is it requires no additional hardware or backbone network. The mobile companies have already put the infrastructure in place and all that is required is to establish an account. In the maritime domain this transmission channel is only limited by the coverage of local network providers and is usually robust in areas of major metropolitans. Major harbors like New York have good coverage while areas offshore generally become degraded beyond a few miles. As GPRS coverage is lost satellite communications offer an alternative viable transmission channel alterative.

## F. SATELLITE

Satellite transmission, while not perfect; offer a tremendous coverage area compared with GPRS. A satellite signal has the singular advantage of providing a communication link while at sea away from terrestrial GPRS networks or in areas of poor

GPRS reception. It offers both single point-to-point communications as well as the ability to integrate with a local network to provide connectivity and backhaul capabilities. The satellite channel can act as a stand-alone link and provide connectivity in remote areas outside of normal mobile service coverage. This is important in the maritime domain where commercial cell phone coverage has limited range from the shore. As an LOS system, requiring a clear view of the sky it is a poor choice for communications below deck. However, it is excellent for providing a viable backbone for network traffic in conjunction with other locally deployed radio networks. NPS utilizes a SWE-Dish terminal for connectivity (See Figure 8) and will be utilized for the satellite link during experiments. The system can be susceptible to interferences as experienced in New York during periods of heavy rain.


Figure 8. SWE-DISH Satellite (Retrieved March 2009, from http://www.swe-dish.com/products/suitcase-systems.html)

## G. SA MULTI AGENT SYSTEM

Eugene Bourakov and Dr. Bordetsky at the NPS developed the SA Multi Agent System in 2002 for the purpose of increasing battlespace awareness for personnel in the field and unit commanders (Klopson & Burdian, 2005). The SA Multi Agent System is

used by NPS in conjunction with their TNT MIO experiments. The primary focus of these experiments have been to increase battlespace awareness through innovative networking topologies and learning how to best incorporate the data into collaborative tools to enhance situation awareness.

The SA Multi Agent System is a client-server application. The combination of Macromedia shared objects and client-server architecture allows the system to provide a dynamic and content rich interface. The SA Multi Agent System is database driven allowing it to constantly update as new information is received. All events are relayed from the agent to the server where they are stored in database tables and then pushed out to sync with all the other agents (Klopson & Burdian, 2005). The system is web based providing a user friendly Graphic User Interface (GUI) (See Figures 9, 10, 11) and may be accessed from any device with connectivity to the network. As the SA Multi Agent System has matured so have the capabilities. The addition of Google Earth to the SA Multi Agent System provides a dynamic tool for displaying GPS data. The Google Earth component of the SA Multi Agent system is what this thesis will be primarily focused on but the SA Multi Agent System provides two-way communication and a wealth of additional information to enhance situational awareness. The Google Earth component of the system is what will be utilized to process the GPS tracking data that is transmitted by the various communication channels. An excellent overview of the entire SA Multi Agent System is provided in a NPS Thesis by Klopson and Burdian. GPS tracking data is received from the agent as a NMEA file. A script parses the file and stores on the NPS server database. Google Earth KML can be generated, time stamped and displayed real-time through the Google Earth SA Viewer. The advantage of this architecture is it allows all clients to view and receive updating tracking information from any device connected to the network. The only real limiting factor is connectivity. The location information and date stored in database may also be recalled at anytime and replayed through the SA Replay Control portal. This is advantageous for post analysis of an operation and provides the ability for users to update track information if they temporarily loose connectivity.


Figure 9. CENETIX Resource Portal

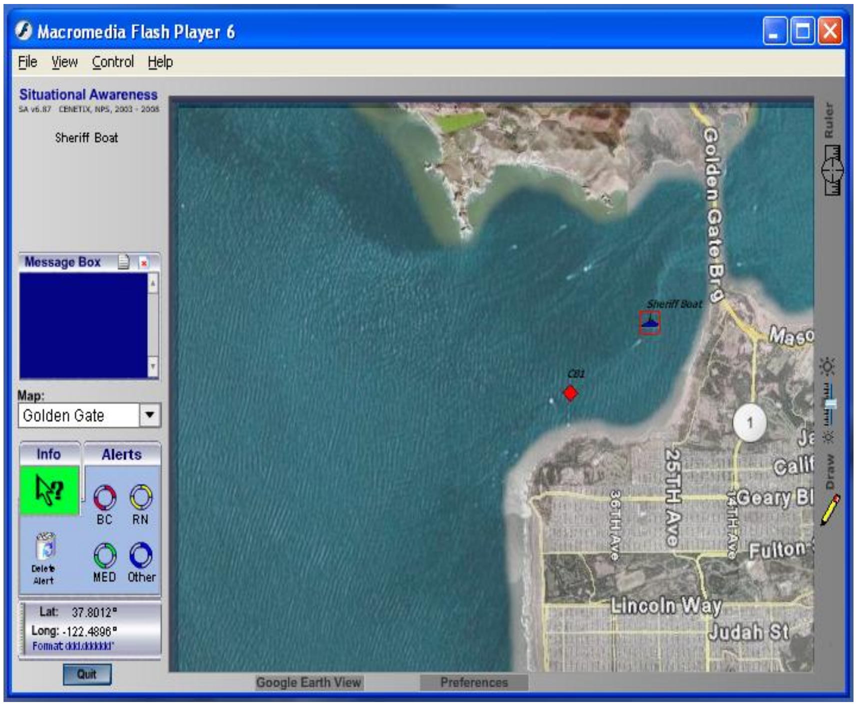


Figure 10. SA Control Agent

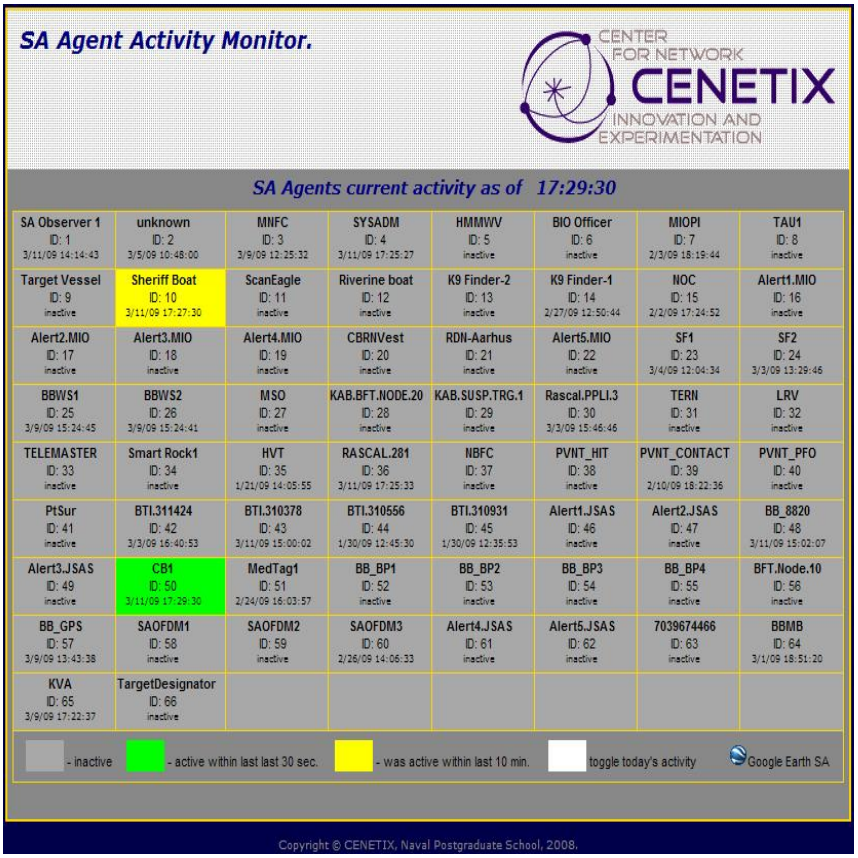


Figure 11. SA Agent Activity Monitor

# V. GPS TAGGING AND TRACKING OF VEHICLE

## A. NAVAL POSTGRADUATE SCHOOL FIELD EXPERIMENT TNT MIO 08-2, EUROPE

This experiment will test the feasibility of combining GPRS and satellite communication channels with a GPS receiver and test its interoperability with the Google SA viewer. A vehicle is stopped at a simulated checkpoint in the Bavarian Alps after detection of a possible radiation source. The passenger Biometric data is taken and uploaded to the fusion center and the vehicle is tagged for further monitoring. This vehicle will be monitored as it crosses through Europe and a variety of different geographic regions. Although the tagging does not take place in the maritime environment the experiment allows us to evaluate the performance of the GPS receiver working in tandem with two different communication channels. This experiment also demonstrates the capability provided by fusing satellite links with GPS receivers in isolated regions, not unlike the maritime environment where access to terrestrial communication links are often non-existent.

## B. DATE

4-6 March 2008

## C. LOCATION

Germany, Sweden, Poland, UOB Command Post and NPS CENETIX MIO TOC

## D. BACKGROUND

The Coast Guard has the ability to monitor vessels equipped with AIS as they near shore. The AIS system works as an LOS digital VHF-FM radio self-organizing LAN. All users within radio range know where each is and autonomously and continuously send each other navigation messages. Each AIS transponder is programmed with the ship's specific information to identify itself to other ships and to authorities.

Regulation 19 of the International Maritime Organizations (IMO) International Convention for the Safety of Life at Sea (SOLAS), Chapter 5 requires that AIS shall:

- Provide information - including the ship's identity, type, position, course, speed, navigational status and other safety-related information automatically to appropriately equipped shore stations, other ships and aircraft
- Receive automatically such information from similarly fitted ships
- Monitor and track ships
- Exchange data with shore-based facilities.

The U.S. Coast Guard is working to upgrade their AIS system as part of the NAIS acquisition project and is being rolled out in three Increments (See Figure 12).

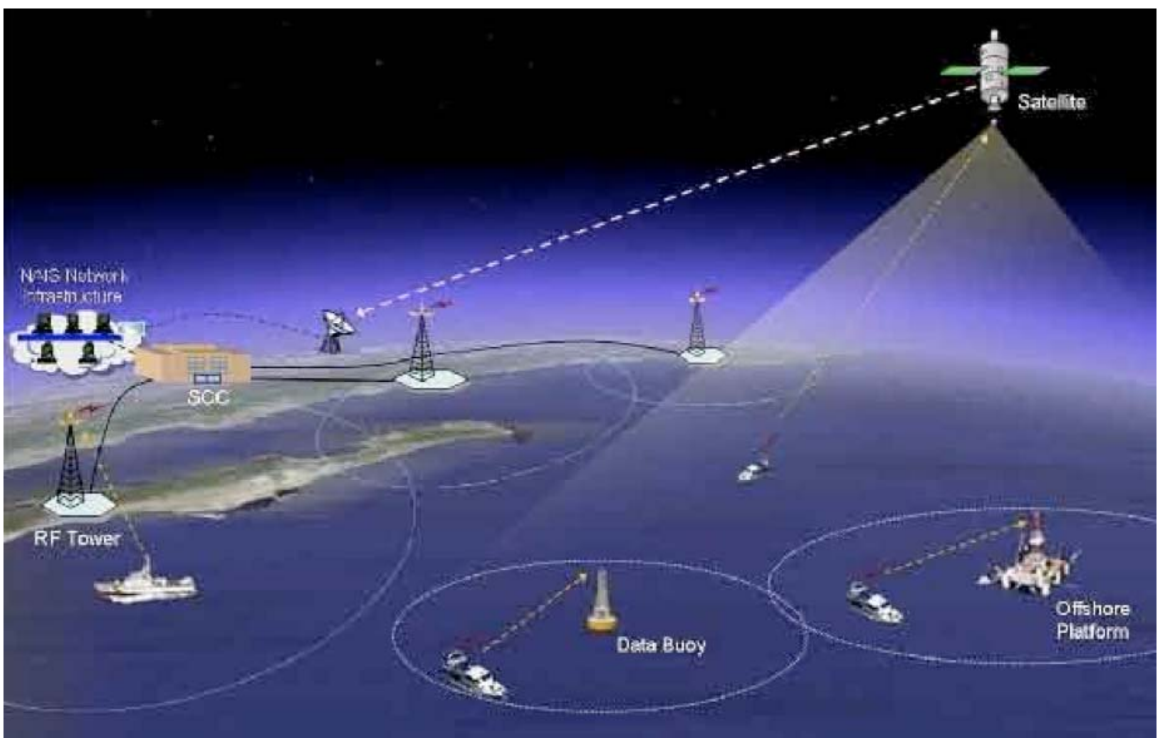


Figure 12. U.S. Coast Guard NAIS Architecture (Retrieved March 2009, from http://www.uscg.mil/ACQUISITION/programs/pdf/NAIS.pdf)

The first Increment was declared complete in September 2008 and provides AIS receive capability within the nation’s 58 highest priority critical ports and 11 coastal areas. Increment II will expand receive capability out to 50 nautical miles and transmit

capability out to 24 nautical miles. The contract for Phase one of Increment II was awarded in December 2008. Requests for Proposals (RFP) for phase two of Increment II are expected to be announced in 2010. Increment III calls for integration of Very High Frequency (VHF) and satellite links to provide AIS coverage out to approximately 2000 nautical miles as detailed in Figure 10. As of Dec 2008, there was no expected completion date for when the third Increment of the system to be fully operational (U.S. Coast Guard Office of Navigation Systems, 2009).

In addition to the U.S. Coast Guard plans to increase coverage area there is an international effort to expand monitoring capabilities of vessels on international voyages. In 2006 the Maritime Safety Committed adopted regulations for Long Range Identification and Tracking (LRIT). This is a mandatory requirement for certain vessels on international voyages and is required of ships constructed on or after 31 December 2008 with a phased-in implementation schedule for ships constructed before December 2008 (International Maritime Organization, 2009).

While each system provides the ability to monitor and track vessels, their effectiveness is reliant on trust of the operators. This trust is based on the premise that the AIS or LRIT transponder is on the correct ship and the operators of the vessel leave the transponder on. Disabling the transponder is a simple matter of turning the transponder off to mask position. The AIS transponder could also be used to mislead law enforcement agencies by swapping transponders with a second registered vessel. AIS, while more mature then LRIT, is limited by the range of its VHF radio. As the vessel departs the VHF radio range of shore (approximately 30-40 nautical miles), the ability to track and monitor with AIS is no longer available. LRIT offers the capability of monitoring much greater distances but is still a young program and not widely in use. As a result of these limitations and vulnerabilities, the ability to tag and track a vessel from point A to point B, unbeknownst to the operators, provides an extra level of security. While it’s not practical to tag every single vessel, long-range tracking, fused with specific intelligence, provides real-time tracking of a vessel or cargo when tracking is warranted. The following scenarios test the feasibility of placing such a GPS tracking device on a vehicle and monitoring its progress.

## E. EXPERIMENT TECHNOLOGIES

- Google Earth SA Viewer used to track and monitor electronic tag. Each KML file specifies position via longitude and latitude in addition to a set of features (place marks, images, polygons, 3D models, textual descriptions, etc.) for earth view applications.
- TNT Observer Notepad
- VC Tools
- GPRS/Iridium GPS Tag

## F. GEOGRAPHICAL VARIABLES

- Bavarian Alps
- Baltic Sea

## G. MEASURES OF PERFORMANCE

- Ability to track vehicle from point of tagging to final destination
- Ability of tag to switch between GPRS and Iridium satellite communication channels
- Ability of SA Multi Agent to receive and display KML files into the Google Earth viewer

## H. EXPERIMENT HARDWARE AND SOFTWARE

### 1. GPS Tag

- Pelican Case
- GPS receiver
- GPRS transmitter
- Iridium satellite transmitter

Figure 13. Pelican case with GPS receiver and GPRS/Iridium

### 2. SA Multi Agent System

- TNT VPN
- TNT SA Server
- Google Earth SA Viewer

## I. SCENARIO

The TNT-MIO experiment was conducted to evaluate several different new technologies in the realm of networking and collaborative tools. For the purpose of this evaluation, the paper will be focusing on the effort to tag and track a target of interest as it travels from Germany to Sweden. In this case the target of interest will be a vehicle and is identified as High Value Target (HVT). The route of the HVT will take it through the Bavarian Alps to Gdynia, Poland where it will take a ferry for the transit to Karlskrona, Sweden across the Baltic Sea. The HVT will be identified as suspicious by a simulated checkpoint in the Bavarian Alps. The tagging device is placed in the trunk of

vehicle and will be monitored at a small command post at the University of Bundeswehr (UOB), Munich Germany and the SNWC MIO team in Karlskrona. All activity and issues will be addressed through the NPS TOC.

**1. 04 Mar 09 (log taken form Observer Notepad)**

0900 Local Monitoring phase of experiment begins

1052 HVT departs UOB (simulated checkpoint) and is traveling on the Autobahn

1108-1113 Signal is lost indicating possible problem with GPRS

1119 Still issues with signal, report from team that they are switching to Iridium satellite connection

1134 Tracking is back on line and has been good for 40 minutes

1200 Despite a few minutes of lost signal, UOB has been tracking HVT for an hour and HVT is nearing checkpoint

1224 Contact of mobile team reveals possible intermittent signal drops may be due to travel through tunnels

1225 HVT at checkpoint

1304 Experiencing a loss of signal of almost 20 minutes reported (longest outage of the day)

1321 Mobile teams reports re-setting sensor and signal is restored

1353 Connection with Iridium satellite appears to be down again and has been interrupted since 1327.

1450 Signal loss for four minutes

1621 Vehicle signal is back online after over two hours, Possible restart of sensor reported

1650 Signal loss for four minutes

| | |
|---|---|
| 1657 | Signal loss for four minutes |
| 1838 | Both GPRS and Iridium links are down |
| 1925 | Iridium link re-established |
| 1930 | Iridium Link lost, switching to GPRS |
| 1950 | Link up |
| 2122 | Ling down, no connection from GPRS or Iridium |
| 2222 | Link is back up |
| 2240 | Satellite link down but posting over GPRS |
| 2312 | HVT parked for night |

**2. 05 Mar 09**

| | |
|---|---|
| 0956 | HVT on move and posting via GPRS |
| 1138 | Signal has been good with GPRS, Iridium still down due to problems with SBC |
| 1330 | HVT crossed Polish Border |
| 1345 | Switched GPRS provider from Vodaphone to AT&T, signal still good |
| 1815 | HVT arrives at Gdinya ferry terminal |
| 2000 | HVT boards ferry |

**3 06 Mar 09**

| | |
|---|---|
| 0916 | Ferry arrives in Karlskrona, signal was strong during entire ferry crossing |
| 1345 | Iridium GPS poster is back up, cause of failure was due to corrupted Operating System on the SBC Compact Flash (CF). CF was swapped out. |

1400 HVT traveling to Malmo, Sweden. Posting GPS over Iridium

1730 Arrived Malmo, cease exercise

## J. PERFORMANCE EVALUATION

The ability to track a HVT with GPS and the fusion of a satellite and GPRS communication channel has proved very effective. Both operations centers were able to monitor and track the HVT through the Google Earth SA viewer in real-time as can be seen in this close up of the HVT traveling through Germany (See Figure 14). However, there were drops in connectivity between the GPS sensor and NPS servers (See Figure 15). This loss of connectivity was a combination of GPS signal loss, GPRS signal loss, and the inability to transmit data via the Iridium satellite service. As with any type of hardware, electrical components are prone to failure. The best way to overcome this possibility is through the use of redundant systems. In this scenario the problem was identified with the Iridium Single Board Computer's (SBC) corrupted CF. In a real world scenario, this replacement would not have been possible and highlights the need for redundancy.

The loss of GPRS and GPS signals can be contributed to geographical factors as the HVT traveled through mountainous regions. A visual representation of this period of signal loss compared with route traveled can be observed in Figure 16. The blue line represents a working signal and the red line represents a lost signal. Geographical contours of an area obviously present a problem when working in a terrestrial environment. However, when taken in the context of a marine application, this experiment proved very successful. As vessels transit the world oceans, they are free of these types of geographical obstructions that prohibit a clear view of the sky. In fact, there was 100% connectivity as the HVT crossed the Baltic Sea via ferry. While traveling the oceans, vessels are provided clear LOS views of the satellites. An onboard GPS receiver and satellite should have none of the connectivity issues encountered during this experiment. As the vessel approaches shore, GPRS signals would kick in and act as a redundant communication channel. The vessel should also become visible on the U.S. Coast Guard COP through the AIS system. If the AIS signal and tagging device showed

any type of discrepancy, this would provide a clear indication something is wrong, either through intentional misdirection by the vessel or the malfunctioning of one of the devices. This type of discrepancy paired with previous intelligence would provide the Coast Guard Captain of the Port (COPT) clear probable cause to refuse entry into U.S. waters until the vessel has been thoroughly inspected. This type of advanced warning is critical when combating weapons of mass destruction (WMD's). The farther we can keep these types of weapons from our shores, the better chance we have of preventing injury to life or property.

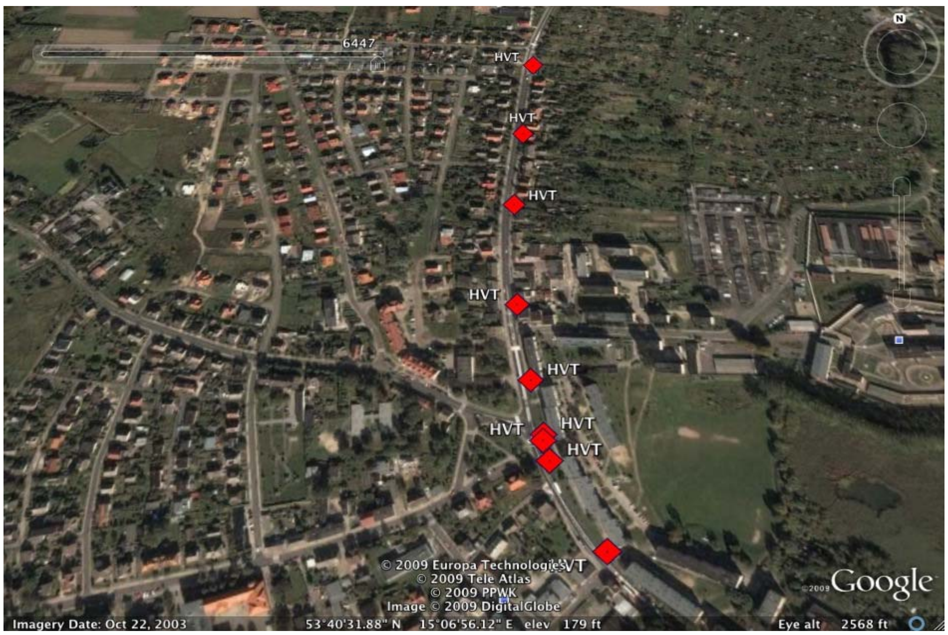


Figure 14. Close up of HVT traveling on the (From SA Replay)

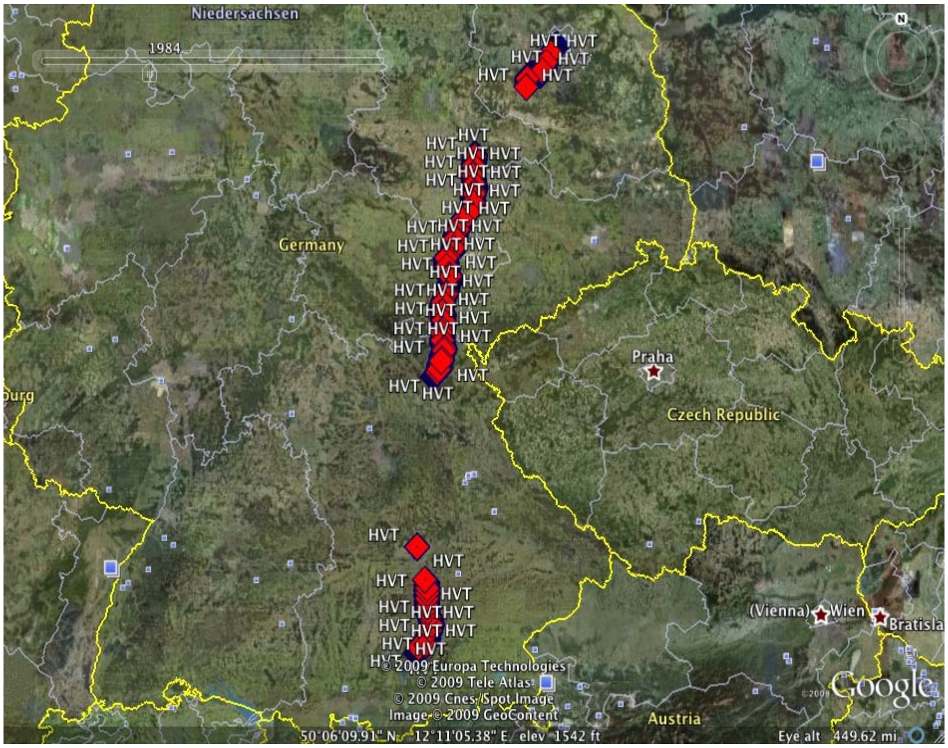


Figure 15. HVT tracks across Germany (From SA Replay)


Figure 16. HVT Route from Neubiberg to Central Munich (From TNT MIO 08-02 After Action Report)

# VI. GPS TAGGING AND TRACKING OF SMALL VESSEL

## A. NAVAL POSTGRADUATE SCHOOL FIELD EXPERIMENT TNT MIO 08-2, CALIFORNIA USA

This experiment explores the feasibility of tagging and tracking small vessels with GPS receivers and posting position data via a 900 MHz wireless communication channel. The communication channel will be established via an aerostat balloon hovering over the Riverine area providing a LOS relay link. A satellite link will be established on shore to provide connectivity to the NPS server. From the MDA perspective, the ability to tag and track smaller vessels is very important as they are currently not required to participate in the AIS system.

## B. DATE

13 March 2008

## C. LOCATION

Sacramento River Delta, NPS CENETIX MIO TOC

## D. BACKGROUND

Current AIS requirements limit mandatory carriage requirements to "Self-propelled vessels of 65 feet or more in length, other than passenger and fishing vessel, in commercial service and on an international voyage…" (U.S. Coast Guard Navigation Center, 2009). AIS is also required for towing vessels of 26 feet or more in length and passenger vessels certified to carry more than 150 passengers-for-hire. Currently, there are no AIS carriage requirements for smaller vessels. This leaves a huge hole in the U.S. Coast Guard's ability to maintain MDA. Small vessels are quick and highly maneuverable and capable of inflicting serious damage as was demonstrated in the 2000 attack on the USS COLE. In the USS COLE attack, a 35-foot vessel laden with explosives rammed a Navy ship, ripping a hole in the hull killing 17 Sailors. The U.S.

Coast Guard is working to plug this gap in MDA with the deployment of sensor systems incorporated in their Hawkeye project. Hawkeye works to improve MDA through the use of strategically placed sensors (infrared cameras and radar) to enhance the overall picture provided by AIS (See Figure 17). The data from these sensors is collected and fed into the COP. The ability to feed tracking data of a smaller vessel of interest not in the AIS system would enhance the tracking capabilities of the COP even further.

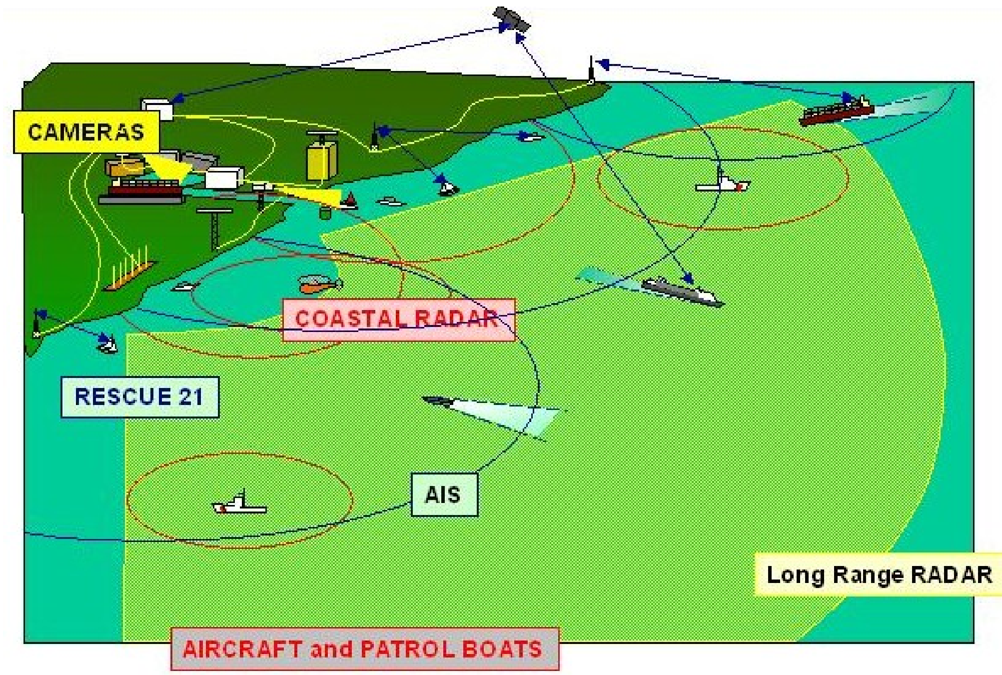


Figure 17. Hawkeye Project (Retrieved March 2009, from http://www.piersystem.com/go/doc/586/40633/))

## E. EXPERIMENT TECHNOLOGIES

- Google Earth SA Viewer used to track and monitor electronic tag. Each KML file specifies position via longitude and latitude in addition to a set of features (place marks, images, polygons, 3D models, textual descriptions, etc.) for earth view applications.
- TNT Observer Notepad
- NPS VC Tools
- Groove
- Wave Relay
- Aerostat balloon

## F. ENVIRONMENT VARIABLES

- Sea State
- Wind

## G. MEASURES OF PERFORMANCE

- Ability to track small vessels
- Ability to transmit position data over communication channels
- Ability of SA Multi Agent to receive and display KML files into the Google Earth Viewer.

## H. EXPERIMENT HARDWARE AND SOFTWARE

- Tachyon satellite
- Sky Pilot Relay
- SA Multi Agent System
- GPS Sensor
- Panasonic Toughbook
- FreeWave 900 MHz Ethernet radios (3 radios)

## I. SCENARIO

Although TNT MIO 08-02 was much broader is scope, this chapter focuses on the Riverine portion of the experiment conducted in the Sacramento Delta. The objective is to establish robust tagging and tracking of small vessels and ship-to-ship/ship-to-shore networking while traveling at high speeds. An Oakland Special Police Boat will deploy the aerostat balloon to provide connectivity on a rapidly-deployable 900 MHz link. This link will give users the ability to transmit and receive data and video back and forth to the NPS TOC. An Adaptable Radiation Area Monitor (ARAM) sensor, installed by the Lawrence Livermore National Lab, will be placed on the Oakland Police Point. Following stand-off nuclear/radiation detection tests of suspect vessel, a high-speed chase ensues to test connectivity and tracking capabilities. While radiation detection is not the focus of this thesis, it’s important to note the demonstrated capability to detect and collaborate with experts at Lawrence Livermore National Lab (LLNL). The

communication link will provide video and nuclear/radiation detection results to LLNL allowing them to make a critical assessment of the threat. In addition, the experiment will test the abilities of the Port Authority New York/New Jersey (PANYNJ) ability to receive and simulate an emergency response to the radiation threat. The full results of experiment can be reviewed in the TNT MIO 08-02 After Action Report.

### 1. 13 Mar 09 (log taken from Observer Notepad and MIO AAR)

| | |
|---|---|
| 0900-1000 Local | Target vessel gets to staring position |
| | Oakland Police Boat deploys aerostat and moves to starting position |
| 1000-1400 | Stand-off nuclear/radiation detection tests begin |
| 1112 | YBI NOC established video feed |
| 1228 | Detection tests have begun |
| 1250 | Riverine chase boat receiving video feed |
| 1252 | ARAM detection device has identified U238 and U232 on target vessel |

## J. PERFORMANCE EVALUATION

The experiment successfully proved the feasibility of deploying a rapidly-deployable wireless network and demonstrating the capabilities it provides. When working, this network successfully established two-way connectivity allowing the transfer of data, video and ARAM detection information. More importantly, for the scope of this thesis, it provided a communication channel allowing the posting of GPS position data. The experiment ran into difficulties, however, as the weather conditions deteriorated. As the winds picked up, the aerostat balloon was driven downwards and LOS connectivity was lost. This loss of connectivity can be see in Figure 18 where there is a demonstrated loss of GPS position data.

An unexpected benefit provided by the difficulties encountered with the aerostat balloon and LOS network was the development of a new solution. As troubleshooting was taking place over commercial cell phones the idea was formed to take advantage of this readily available network for GPS posting. With commercial GSM service available in the Riverine Area, there is no reason why GPRS cannot be utilized.

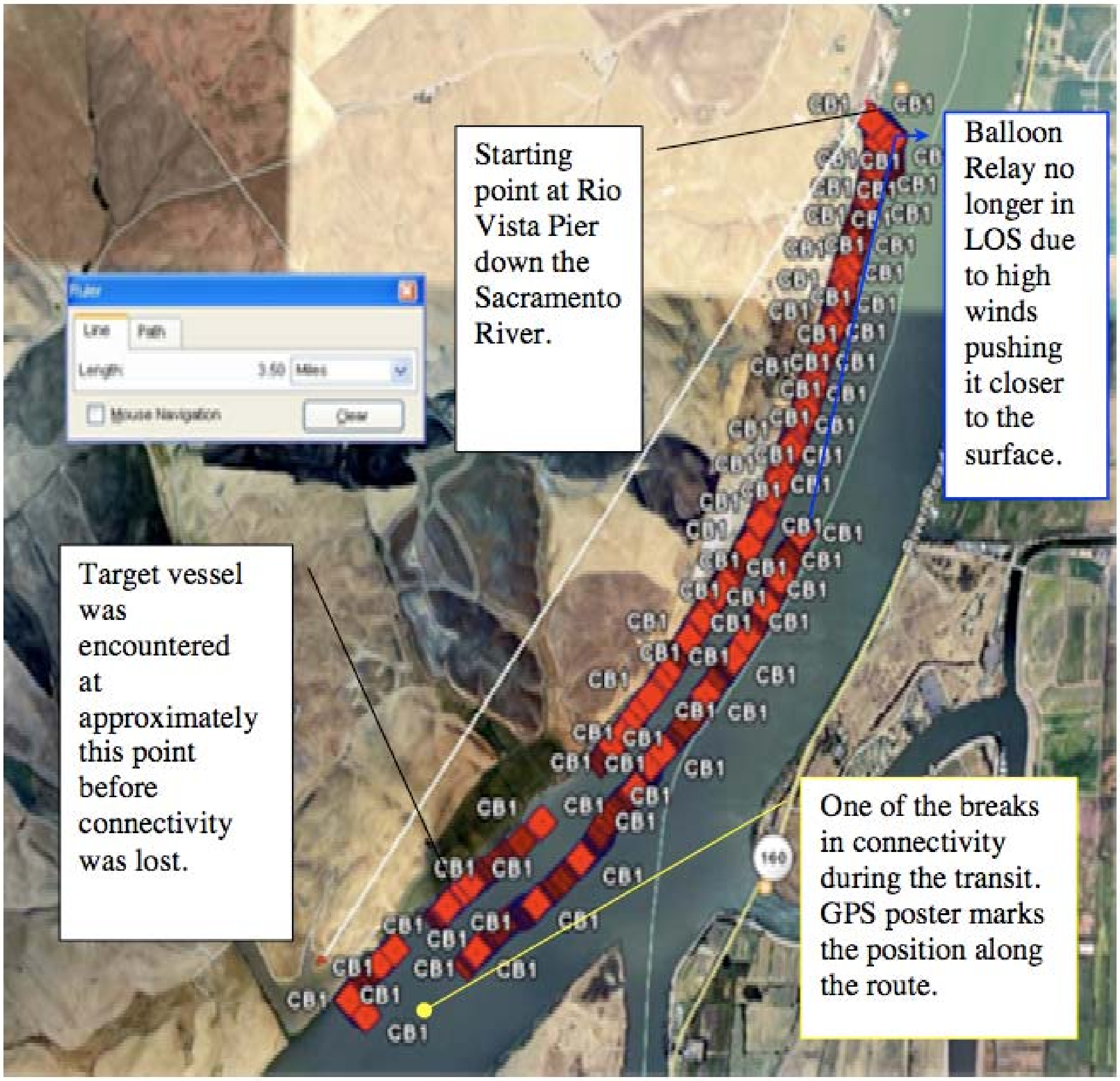


Figure 18. GPS Riverine tracking data (From MIO TNT 08-02 AAR)

The circled device in is the GPS sensor and the blocked device is the FreeWave Radio (See Figure 19) used during the experiment. It was connected to a laptop via USB and was posting positions over the 900 MHz channel via a Visual Basic posting program developed by Eugene Bourakov. With the recent growth of smart phones with built in GPS sensors, the ability to receive and post GPS data can be streamlined into a much smaller package.

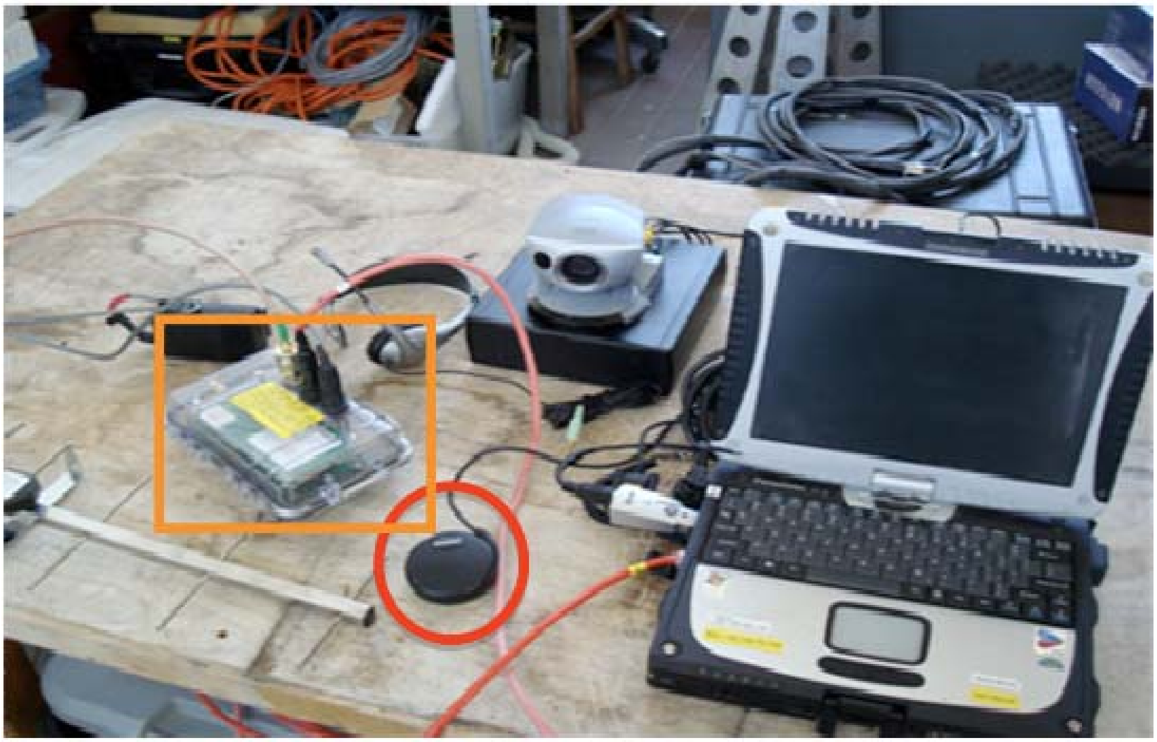

Figure 19. GPS sensor (circle), FreeWave Radio (square) (From TNT MIO 08-02 AAR)

An even greater advantage of the small form factor is when operating in Riverine environments; the chance of a commercial GSM network being available is very good. Utilizing a commercial off-the-shelf Blackberry cell phone (Figure 20) with a built in GPS receiver you can dramatically decrease hardware requirements. Taking advantage of a ready-made communication network (GPRS), this device can post GPS positions directly to the NPS server and eliminates the need for an elaborate communication topology as seen in Figure 21.


Figure 20. Blackberry device

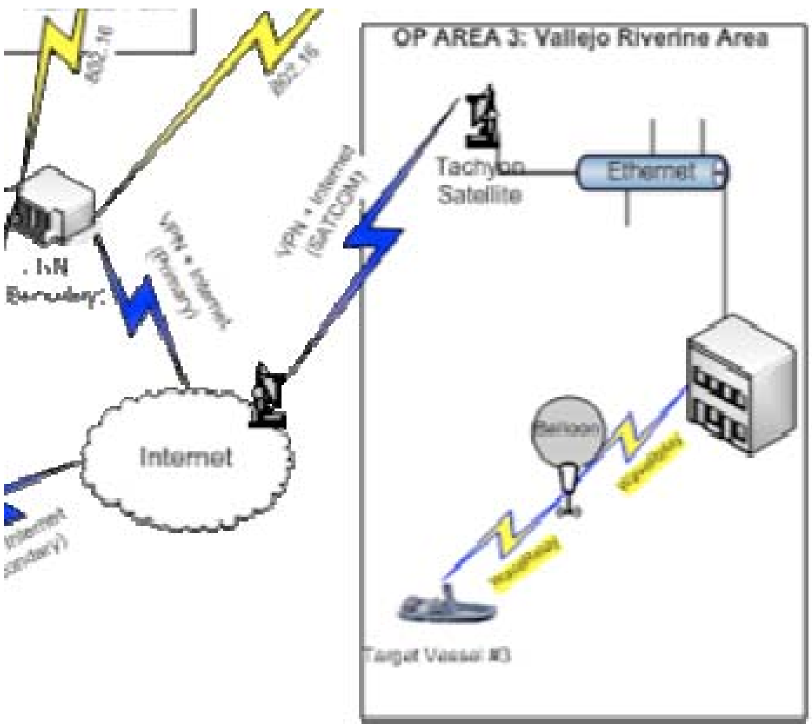


Figure 21. Network Topology for Riverine Area (From TNT MIO 08-02 AAR)

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# VII. CONCLUSIONS AND RECOMMENDATIONS

## A. CONCLUSIONS

### 1. Integrating GPS Data with Collaborative Software Tools

The ability to monitor any type of entity whether it be vehicle, vessel or person in real-time provides a visual tactical picture for the viewer that enhances overall situational awareness. The CENETIX Situational Awareness Agent tool worked well displaying this information, as a collaboration tool, and shared the information across the network. Porting vehicle or personnel tagged GPS data into the Coast Guard COP or any other situational awareness tool would not be difficult. The GPS data files are based on the standard NMEA file format. This NMEA file format is already supported by Coast Guard systems and is used to support AIS vessels tracks and BFT. Incorporating positioning data from a tagged source, either vessel or person, is the next step in the situational awareness evolution. GPS receiver technology has matured to the point, both in terms of its small form size and affordability, that there is no reason not to explore this tagging capability further. Commercial real time tracking is now available and becoming commonplace in the market for the common user through systems like Google Latitude. Any user can use the service to track users through the Google Earth interface utilizing GPS and Cell tower triangulation. Social networking applications for personal mobile devices are capable of doing the same thing. For example, the free smart phone application Loopt continuously updates a users GPS position and allows any registered user to access the position of other registered users directly from their phone. The iPhone by Apple, and Blackberry by Research In Motion (RIM), are revolutionary devices. The mix of GPRS connectivity, 802.11 connectivity, support for enterprise architectures and GPS sensors with a robust operating system make these formidable devices with tremendous potential. The phones small form factor, full-featured web browser and unique touch screen interface make the platform an excellent device to pursue further as a collaborative tool.

### 2. GPS and GPRS Communication Channel

GPRS has proven to be a viable solution in Riverine and near shore areas where commercial cell phone coverage is available. The benefit of this pre-built commercial network cannot be overstated in terms of availability and accessibility. GPRS eliminates the need to create or develop any additional infrastructure and is available at short notice. The type of network loss issues experienced with the aerostat balloon during the MIO TNT 08-02 experiment are taken out of the equation, dramatically reducing the network topology requirements.

GPRS does not need to be limited to commercial carriers. NPS has been successful in exploring tactical cellular networks. The tactical cellular network provides a secondary option for rapidly deployable networks and offers the ability to provide GPRS in areas of limited or no commercial coverage. A GPRS router connected to a Redline 802.16 network providing reach back to the TOC is pictured in Figure 22. This system utilizes a standard Subscriber Identity Module (SIM) cards that can be placed into any unlocked cell phone or SIM card reader. In Figure 22 the laptop has connectivity via the tethered cell phone. The cell phone, with CENETIX SIM card (See Figure 23), is connected to the tactical cellular network. While this type of network can be limited by topography in ground or urban environments it may prove successful in the maritime environment and warrants further exploration.

Figure 22. Tactical Cellular Network (From Camp Roberts, CA)


Figure 23. CENETIX SIM Card

### 3. GPS and Satellite Communication Channel

Satellite communications provide a viable communication channel in non-GPRS service areas. Although connectivity is slower than GPRS, resulting in less frequent GPS postings, it is more than sufficient for long-range tracking. The tandem use of Satellite and GPRS provides a one-two punch that solves the open space connectivity issue.

## B. RECOMMENDATIONS FOR FUTURE RESEARCH

### 1. Tracking of Personnel below Deck in GPS Denial Areas

As discussed above, the ability to tag and monitor with GPS in the open environment is a proven capability. The next step in the research is to develop alternative methods of determining position when operating in a GPS denial area. One of the most promising areas is the tandem use of inertial navigations systems with GPS receivers. Initial research was conducted in 2007 with NPS and CHI Systems and their SUSA system. The experiment demonstrated the ability of the SUSA system to enhance situational awareness through live position updating utilizing both GPS sensors and an IMU. The system was able to track and update positions of personnel while operating in a GPS denial area located inside a building. Although the IMU offered promising tracking capabilities the SUSA system is a stand-alone product and does not provide collaborative tools that can integrate with other systems. Team members could see them selves but the system was no able to incorporate this data outside its own network. (Bordetsky et al., 2007).

NaviSeer, a new product developed by Seer Technologies, was introduced during the first quarter of 2009 and looks very promising at solving the GPS denial dilemma. The device in Figure 24 utilizes a combination of GPS, Dead Reckoning (DR) and propriety algorithms to produce real-time position updating based on motion to accuracy levels of less than one meter. It incorporates three gyros, three accelerometers, a magnetometer and a barometric altimeter. The GPS and DR data are blended by an internal Kalman filter to provide position updating. The company claims the barometric altimeter provides vertical positioning accurate enough to identify the floor of a building.

This would be extremely beneficial if it could translate into deck level isolation on a large vessel. The device is easily integrated with wearable computers and easily integrated with other electronics (Seer Technology, 2009). If the NaviSeer product can meet the company claims it is an excellent candidate for further research.


Figure 24. NaviSeer (Retrieved March 2009, from http://www.seertechnology.com/naviseer.html)

### 2. Transmitting Personnel Position Data while below Deck

If a viable positioning solution can be developed in GPS denial areas, future research is needed to explore the below deck communication channel. Promising research was conducted during TNT MIO 08-02 utilizing UWB radios integrated with on-the-deck mesh and ship-to-ship broadband wireless network. Using 802.11 Wave Relay as the wireless communication channel, Biometric data could be passed from two decks below on the 441 foot Liberty Ship SS Jeremiah O'Brien. It's important to point out the SS Jeremiah O'Brien is a vintage WWII ship constructed mostly of wood but the experiment demonstrated the potential of USB and Wave Relay. Herb Rubens from

Persistent Systems, developer of Wave Relay, stated the network had 1 to 3 Mbps data transfer rates with only two nodes. He felt with the additional staging of more Wave Relay nodes this performance would be greatly improved (Bordetsky et al., 2008). It would be very beneficial to test this network topology with position data.

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